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DESIGN & FLIGHT TEST RESULT OF A SMALL SCALE HYBRID VTOL UAV

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ABSTRACT

Installing a quad copter in H-configuration onto the wings is one of the ways to introduce vertical flight to a fixed wing UAV. Forward flight is attained by tilting the motors to create forward thrust. This paper discusses the design considerations for the Hybrid VTOL UAV and presents the results from flight tests. The motors are electric and powered by Lithium-Polymer batteries. XFLR5 is used to calculate the aerodynamics variables of the design. Drag and flight endurance is calculated empirically and compared against the real values obtained from flight tests.

KEYWORDS: *Hybrid VTOL UAV, Lithium-Polymer Batteries & XFLR5*

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Original Article

INTRODUCTION

Fixed-wing Unmanned Aerial Vehicles (UAVs) capable of Vertical Take-off and Landing (VTOL), also known as Hybrid VTOL UAVs are a topic of greater research interests in recent years both in academic as well as industrial fields[1,2,3,4]. Attaching a boom on each of the wings that hold a motor and propeller at each of its end for vertical flight seem to be a very simple, yet innovative idea to make a fixed-wing UAV fly vertically.

In an attempt to evaluate its performance, Duo Drone, a Hybrid VTOL UAV was designed and test flown by SAMCO in collaboration with Gyeongnam National University of Science and Technology in Jinju, South Korea. Duo Drone is 1.7m long and has an all-moving tail in conventional configuration. It has a wingspan of 2.2m and Aspect Ratio of 9.3. During forward flight, the aircraft is propelled by only the front motors which tilt forward 90 degrees with a mechanism actuated by an electronic servo while the rear motors are fixed and stopped on the motor mount. Glass/Carbon Fiber-reinforced Plastic (G/C FRP), plywood, Expanded Polypropylene (EPP) and some 3D printed parts are used to manufacture Duo Drone. Its size and basic dimension are shown in Figure 1. The motors are all electric and powered by Lithium-Polymer (Li-Po) batteries. Winged aircraft in conventional configuration with booms for quad copters attached to the wing is designed, manufactured and test flown. Chords of the wings are non-linearly distributed in span wise direction. This configuration gives more wing area compared to a straight tapered wing for the same span and root and tip chord lengths. An all-moving horizontal tail is employed for pitch control. This paper presents the basic designed aerodynamic parameters of Duo Drone and compares actual with the designed flight time.

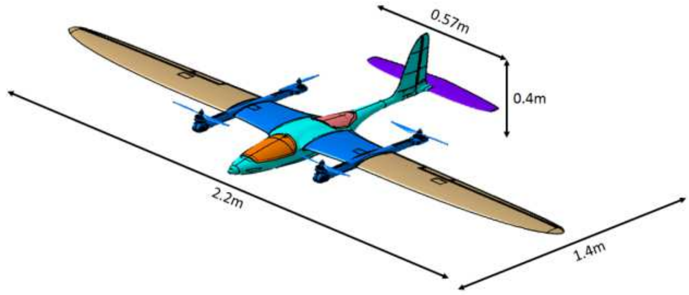

Figure 1: Duo Drone Dimensions

Aerodynamic Analysis

Aerodynamic analysis of Duo Drone is performed using th**e** panel method code XFLR5[5]. Only the Wing and Tail is coupled to simulate the lift and moment characteristics. SG6043 is used for the wings and NACA0011 is used for vertical and horizontal tail. Drag due to the fuselage, booms and other components are estimated empirically. The obtained results are merged and the aerodynamic characteristics are estimated.

Non-linear wing, horizontal tail and vertical tail plan form are divided into 10 panels each for the ease of simulation in XFLR5. Figure 2 shows the panels fitted into the wing, vertical and horizontal tail half-span. Figure 3 shows the simulation model in XFLR5. The UAV is designed to cruise in low Reynolds number regime, typically in the range of 200,000 to 500,000. Simulations are performed on Duo Drone weighing 4.2kg in the flight speed of 11m/s ~ 25m/s in standard atmospheric condition for varying angles of attack. Figure 4 shows the C_L-vs-*AoA* result obtained from XFLR5.

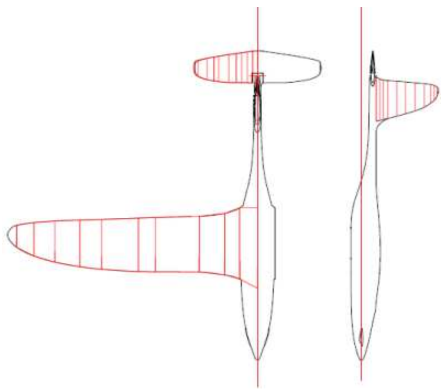

Figure 2: Panels for the Wing and Tails Used for XFLR5 Simulation (Red: Panel, Black: Actual Shape)

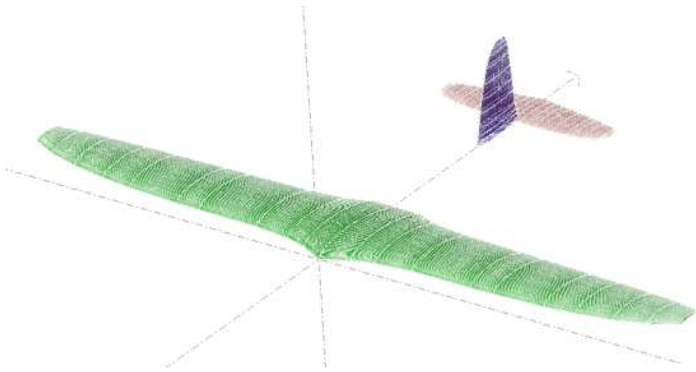

Figure 3: XFLR5 Simulation Model

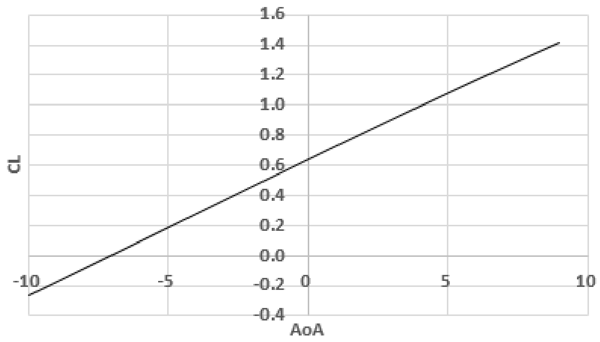

Figure 4: C_L-vs-*AoA*at 14m/s Obtained from XFLR5

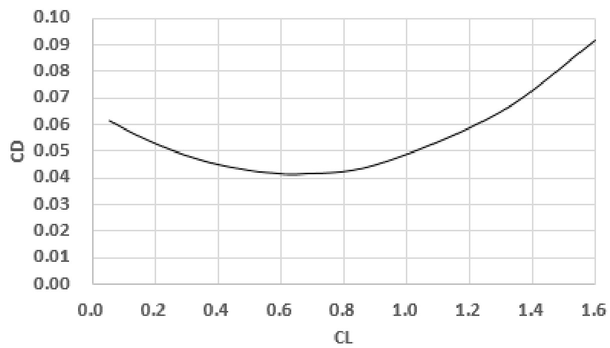

Figure 5: Drag Polar

Aircraft specifications are tabulated in Table 1. Planform efficiency, "e" is estimated to be 0.6 and the induced drag correction factor, "*k*" is computed from "*e*" according to eqn. (1). Zero-lift drag coefficient ($C_{D,0}$) is estimated using the empirical method as described in [6].

Table 1: Aircraft Specification

Mass(m)	Wing Area(S)	Wing Span(b)	Aspect Ratio(AR)
4.2 kg	0.0.52 m^2	2.2 m	9.3

Table 2: Zero-Lift Drag (CD, 0) Contribution of Aircraft Parts

Fuselage	Wing	Vertical Tail	Horizontal Tail	Tilting Booms	Total
0.00352	0.02252	0.00165	0.003	0.00188	**0.03444**

The $C_{D,0}$ contribution of each of the parts are shown in Table 2. Based on these values, the drag polar is plotted in Figure. 5 and the drag polar equation is as shown in eqn. (2).

$$k = \frac{1}{\pi e AR}, \tag{1}$$

$$C_D = 0.0413 + 0.0563(C_L - 0.65)^2, \tag{2}$$

Endurance is estimated based on the work of Lance W. Traub [] and the relationship is as shown in eqn. (3) below

$$E = R_t^{1-n}\left[\frac{\eta_{tot} V \times C}{\frac{1}{2}\rho U^3 S C_{D0} + (2W^2 k/\rho U S)}\right]^n, \tag{3}$$

Where, *E* is the endurance measured in hours, n is the discharge parameter which is dependent on the battery type and temperature, R_t is the battery hour rating in hours, is the discharge current in Amperes, *C* is the battery capacity in ampere hours, *V* is battery voltage in volts, ρ is the air density, S is the wing area, W is the aircraft weight, k is induced

drag correction factor and C_{D0} is the zero-lift drag coefficient. The propulsion system specification is shown in Table 3. Figure 6 shows the flight endurance at varying airspeed. At the target speed of 13m/s, the UAV is expected to cruise for about 75 minutes.

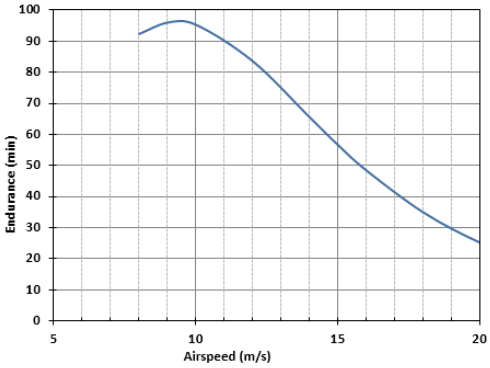

Figure 6: Flight Endurance Estimation at Varying Airspeed

Table 3: Propulsion System Specification

Discharge parameter, n	1.3
Battery capacity, C	8.5Ah
Propulsion system efficiency, η_{tot}	60%
Battery hour rating, R_t	1hr
Battery voltage, V	14.8V

Flight Test Equipment and Method

Duo Drone is equipped with SAMCO's Flight Control Computer (FCC), which has Inertial and Air data Sensor integrated into it. A 4-hole Pitot-tube is installed onto the fuselage nose and a GPS antenna is installed on the inside of the fuselage. A 6-cell 8,500mAh battery powers the motors during flight. An ampere-meter is installed onto the wire of the propulsion battery and is connected to the FCC, which reads and sends the ampere consumption data to the ground. Weighing at 4.2kg Duo Drone is flown in two ways, external pilot mode which uses a RF Modem (915MHz) and internal pilot mode, which uses 2.4GHz frequency signal. The in flight and ground control systems are shown in Figure 7.

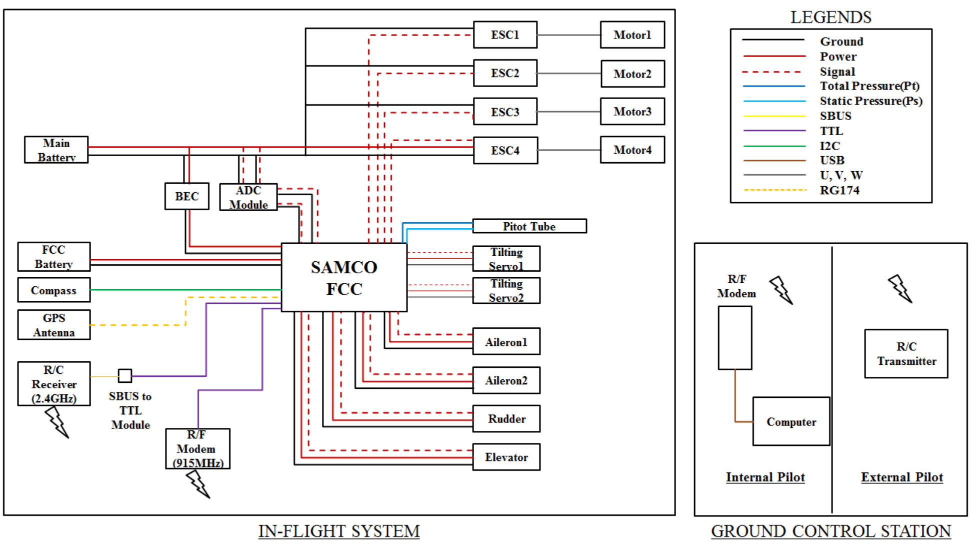

Figure 7: In-Flight & Ground Control System Configuration

Take-offs and landings are performed in external pilot mode and the tests are performed during cruise flight in internal pilot mode. SAMCO FCC has implemented Stability Augmentation System (SAS), Control Augmentation System (CAS), inner loop and autopilot outer loop using the PID control law as the flight control algorithm. In the CAS mode, the aircraft maintains the heading, altitude and speed as per the command. Tests are performed at an altitude of 100m and 13.5m/s speed and in straight path such that the aircraft is flying in visual line of sight. The design criteria set for the selection of gain are as shown in Table 4.

Table 4: Gain Design Criteria

SAS Gain Design Criteria	
Damping ratio	0.707
CAS Gain Design Criteria	
Rising time	0.2 sec
Settling time	1 sec
Steady state error	10%
Autopilot Gain Design Criteria	
Vcmd steady state error	±1 m/s
Hcmd steady state error	±2 m

RESULTS

Endurance Test

Duo Drone successfully completed a total flight-time of 51min. Figure 8 shows the 3D flight trajectory result plot. Figure. 9 shows the flight velocity and altitude. Flight is performed at a speed of 13m/s and at an altitude of 100m. The command is shown in red lines and the aircraft response in blue. Figure 10 shows the current and power of the motors during the entire flight. Duo Drone uses all four motors during take-off and landing and only two front motors operate in cruise flight. The first minute of the flight represents vertical take-off mode which requires higher current to pass through the motors and hence higher power is achieved by the motors. It is similar during landing, only that the time required to land is less. The aircraft loses altitude and velocity during transition hence cruise flight is performed by taking the aircraft to a higher altitude and at a higher speed. Figure 9 also shows that the transition from vertical take-off to cruise is performed by ascending the aircraft to an altitude and speed of 25m and 7m/s higher than the target cruise altitude and speed respectively. During landing the aircraft descends immediately from cruise altitude.

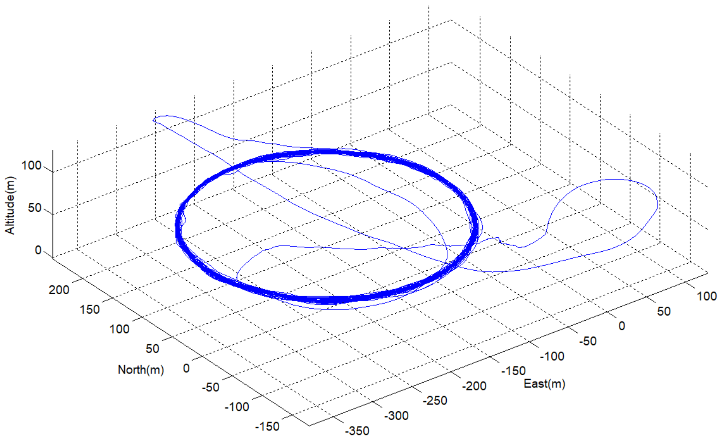

Figure 8: Flight Path (3D Trajectory)

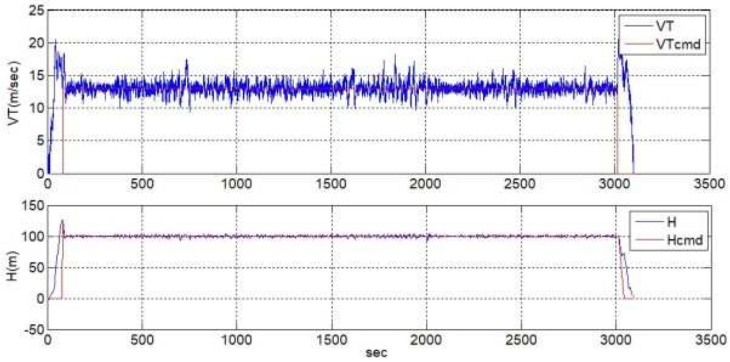

Figure 9: Flight Velocity and Altitude

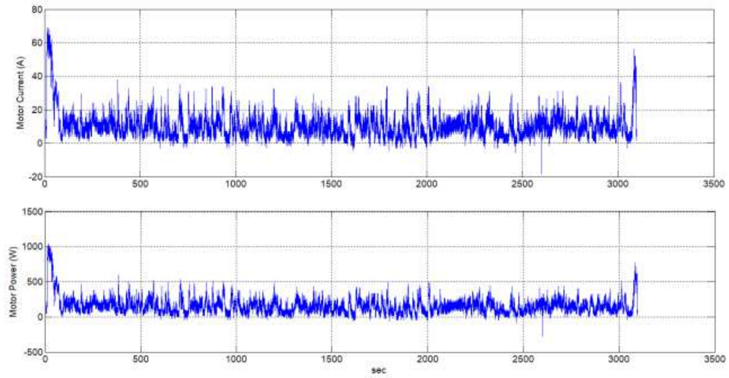

Figure 10: Current and Power of the Motors During Flight

Airspeed, Altitude and Attitude Hold test

Figure 11, 12 and 13 show the ability of the aircraft to follow velocity, altitude and attitude command respectively. Red lines show the command input by the controller and the blue lines show the flight response. Airspeed data is obtained from the barometric sensor and the fluctuations seen in the graph can be attributed to the wind. However, for most of the time the aircraft response is acceptably close to the command input of 13m/s. Similarly, despite the fluctuations altitude response is also in the acceptable range of command input of 100m. Attitude, or the roll (φ), pitch (θ) and yaw (ψ) response of the aircraft is shown in Figure 13, and it can be seen that the aircraft responds very well with the command input.

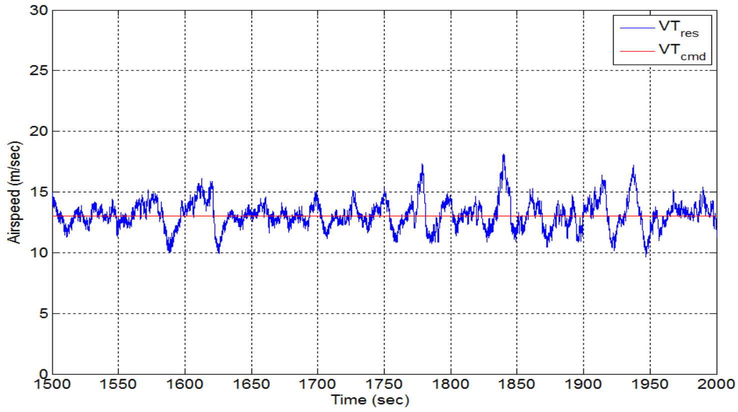

Figure 11: Airspeed Hold Test

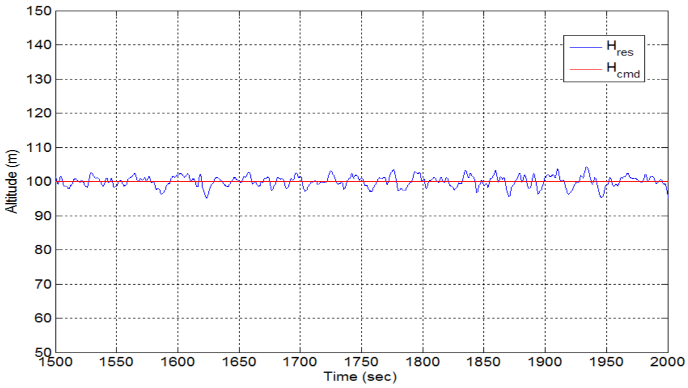

Figure 12: Altitude Hold Test

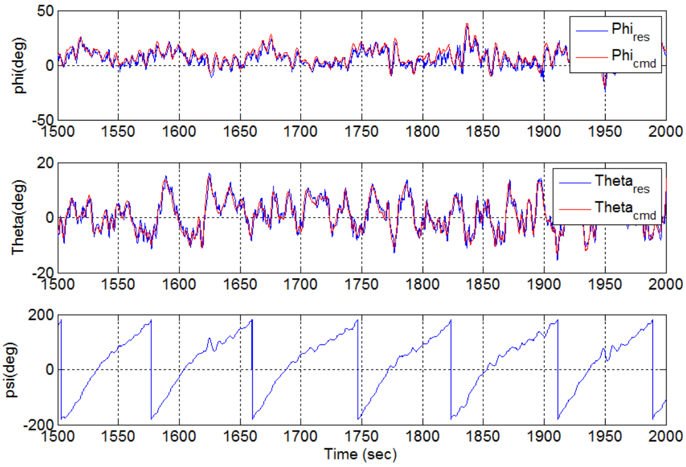

Figure 13: Attitude Hold Test

CONCLUSIONS

SAMCO's flight control computer is successfully integrated into Duo Drone, and a flight time of 51 minutes is achieved at the flight speed and altitude of 13m/s and 100m, respectively. The aircraft is also gain tuned to obtain reasonable and satisfactory response. Obtained flight test result show a 32% deviation from the calculated endurance value. This difference is attributed mainly to the drag generated by the UAV during flights, which were not considered in the calculations.

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